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A SEQUENCE OF SOFT-SEDIMENT DEFORMATION (DEWATERING) STRUCTURES IN LATE QUATERNARY SUBAQUEOUS OUTWASH NEAR OTTAWA, CANADA

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ABSTRACT

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A sequence of soft-sediment deformation structures occurs in Late Quaternary sediments near Ottawa, Canada. The sediments are attributed to deposition on subaqueous outwash fans in the Champlain Sea, at the submerged front of the retreating Wisconsin glacier. In upward sequence the deformed units comprise convolute stratification, ball and pillow structures and dish structures. Deformation is attributed to slumping on the subaqueous fans and/or to the melt-out of ice blocks which had been buried by fan sediments.

The sequence of structures is interpreted in terms of a series of events, as follows: (1) Local fluidization of low permeability sediments formed convolute stratification; disrupted anticlines acted as vertical diapirs through which fluidized sediment ascended; (2) the diapirs penetrated overlying, more cohesive sediments, forming ball and pillow structures; (3) dish structures formed in silty fine sand which had passed upward through the diapirs and between the ball and pillow structures. In some cases the silty sand moved downslope as a liquefied sediment flow and dish structures were deformed to give oval plan forms with long axes normal to the local paleoslope.

INTRODUCTION

Convolute stratification, ball and pillow structures and dish structures are soft-sediment deformation structures which have been observed in the deposits of a wide range of sedimentary environments. The term convolute stratification refers to vertically restricted units which have been deformed into a series of laterally repetitious, broad synclines alternating with narrow anticlinal or diapiric structures. Ball and pillow structures are detached bodies of sand and/or silt which have

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rounded external form, and commonly contain internal stratification bent upwards at their edges. Vertical diapirs may or may not occur between balls and pillows. In addition to detachment, balls and pillows differ from convolute stratification in that they do not necessarily repeat the same lithology laterally within the same unit. Dish structures are defined by Lowe and LoPiccolo (1974, p. 487) as "...thin, dark-coloured, subhorizontal, flat to concave upward lamination...(which ranges in thickness) from clean sharp lines less than 0.2 mm thick to diffuse zones up to 2 mm thick, and in width from less than one to 50 cm".

Forms of convolute stratification have been attributed to cryostatic pressure in the periglacial environment (Sharp, 1942; Washburn, 1956, 1973), gravitational loading (Kuenen, 1958; Davies, 1965; Anketell et al., 1970), rapid dewatering, (Lowe, 1975; Johnston, 1977) and current drag (Sanders, 1960). The formation of ball and pillow structures in most commonly attributed to gravitational loading (Kuenen, 1958) although Butrym et al. (1964) have cited localized liquefaction or fluidization as processes active in their formation. Dish structures are generally thought to form in rapidly deposited sediments by the formation and deformation of fine-grained laminae by escaping pore water (Lowe and LoPiccolo, 1974). Dish structures have been reported in association with primary stratification but the origin of the laminae which undergo deformation is not well understood. A recent review by Mills (1983) summarized the processes which are thought to cause the formation of all these structures.

A striking feature observed in Late Quaternary sediments near Ottawa, Canada, is a vertical arrangement of these three types of soft-sediment deformation structures, which suggests an inter-related origin. Dish structures exposed in plan view have preferred long axes whose orientations are related to the local depositional slope. This paper uses the association of deformation structures near Ottawa to explain relationships between convolute stratification, ball and pillow structures and dish structures.

Setting

The structures described here are exposed in sand and gravel pits in the Stittsville Ridge, approximately 26 km southwest of Ottawa (Fig. 1). The exposures are in the northern part of the ridge, which has been interpreted as subaqueous outwash deposited in a broad embayment of the retreating Laurentide ice sheet, as it terminated in the Champlain Sea approximately 13,000–14,000 yrs B.P. (Cheel, 1982). The term "subaqueous outwash" was introduced by Rust and Romanelli (1975) and comprises the deposits laid down where glaciofluvial sediments are discharged directly from a glacial meltwater conduit into a standing water body, forming a depositional fan (subaqueous outwash fan) well below the effects of the standing water surface. Cheel and Rust (1982) have described the facies of subaqueous outwash based on a detailed sedimentological study of sand and gravel ridges in the Ottawa area. The facies of subaqueous outwash are:

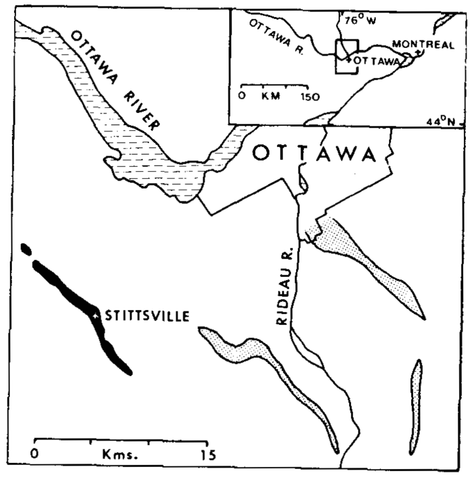

Fig. 1. Map showing the location of the Stittsville R
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(II) Interchannel facies. These depo
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(III) Channel facies. Steep-sided char
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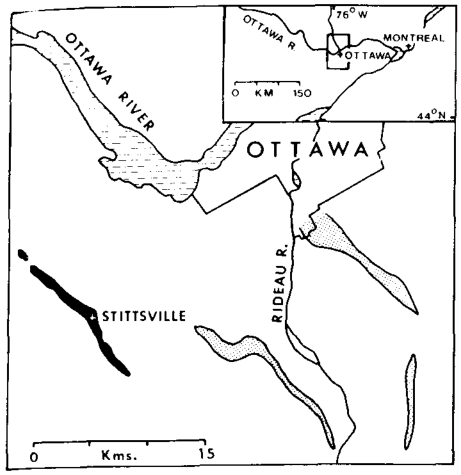

Fig. 1. Map showing the location of the Stittsville Ridge (solid black) and other similar ridges (stippled) of subaqueous outwash in the Ottawa area (after Rust and Romanelli, 1975).

(I) Proximal gravel facies. This facies is deposited at or near the fan apex where sediment is discharged from the glaciofluvial conduit. This includes pebble to boulder size clasts which are imbricate and may have a-axes aligned parallel or transverse to the flow direction, depending on the mode of transport.

(II) Interchannel facies. These deposits are cut by the channels of facies III (below) and vary away from the fan apex. The most proximal deposits are horizontally stratified granular sands (with large clasts ranging up to cobble size) which are believed to have been deposited outside of major channels through which the material of the gravel facies was transported. The coarse grain size inhibits the development of sandwaves and dunes so that cross-stratification is rare in these coarsest interchannel deposits. Further downfan planar tabular and trough cross-stratified coarse to medium sands were deposited with the migration of sandwaves and dunes (respectively) over the interchannel areas of the fan. The most distal interchannel deposits are silty-fine to fine sands which display various types of climbing ripple drift cross-stratification formed by rapid aggradation of a rippled bed on the fan. These deposits extend beyond the reach of the channels where they form thick (up to several metres) sequences. Flow tills and dropstones have also been observed within the interchannel facies.

(III) Channel facies. Steep-sided channels cut the interchannel facies, except for the distal silty-fine sands. Cheel and Rust (1982) described three types of channel fill: (1) horizontally stratified medium sand with imbricate pebbles and cobbles along the base and on bedding planes within the channel fill; (2) massive sands; and (3) horizontally stratified sands. The size of channels tends to decrease upwards in fining-upward sequences, due to their down-fan bifurcation.

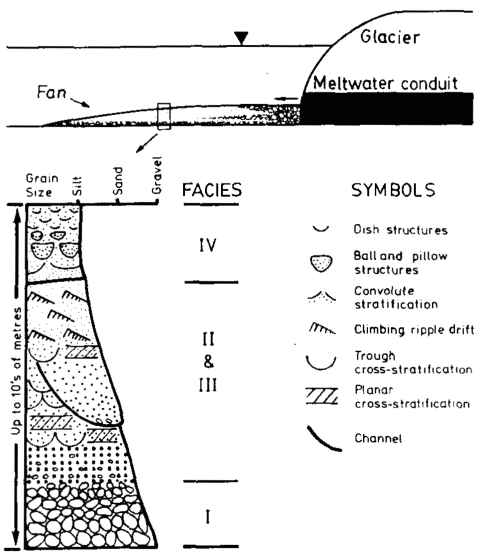

Fig. 2. Highly schematic illustration showing the subaqueous outwash environment (top) and an idealized vertical section through the fan (bottom) showing the sequence of facies that would form as the glacier front retreats (i.e., increasingly distal fan deposits in upward sequence). Note that specific facies are identified by roman numerals which correspond to facies descriptions in the text.

(IV) Slump facies. This facies is developed by deformation of predominantly the silty-fine sand interchannel facies. Deformation takes place under two different circumstances: in rotational slumps on the fan and above sites where glacial ice became buried by the fan and, with melting, caused local fluidization of overlying fan deposits. The soft-sediment deformation structures described in this paper occur in this facies.

Figure 2 is a highly schematic illustration of the subaqueous outwash depositional environment and the facies sequence which develops with the retreat of the glacier front. More complex sequences have been described elsewhere (e.g., Cheel and Rust, 1982; Cheel, 1982) but the sequence shown in Fig. 2 is that which is most commonly observed in the Ottawa area.

DESCRIPTION OF SOFT-SEDIMENT DEFORMATION STRUCTURES

Convolute stratification

In the exposures studied convolute stratification typically consists of broad (up to several metres across) synclines of massive or cross-stratified fine to medium sands. The synclines alternate with narrow diapirs (generally less than 0.5 m across, becoming narrower upwards) composed of silt to silty fine sand (Fig. 3A) and

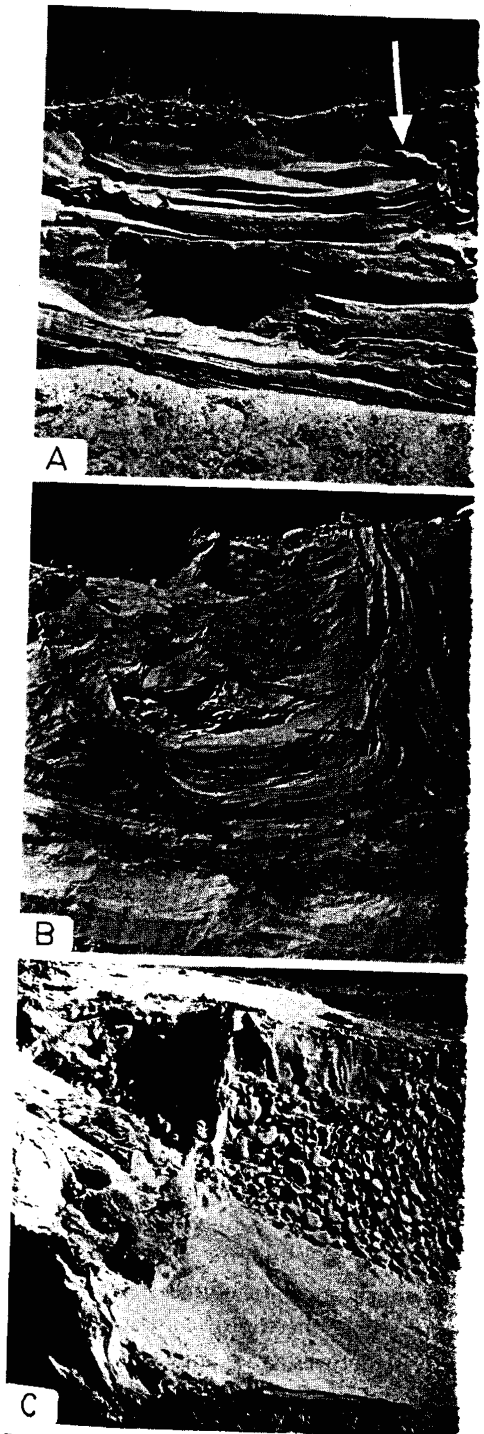

Fig. 3. A. Convolute stratification showing broad extending from the diapir into the synclinal tr convolute stratification displaying subvertical lami of a diapir displaying bubble-like penetrations int filling the synclinal trough has been removed b (diameter 6 cm).

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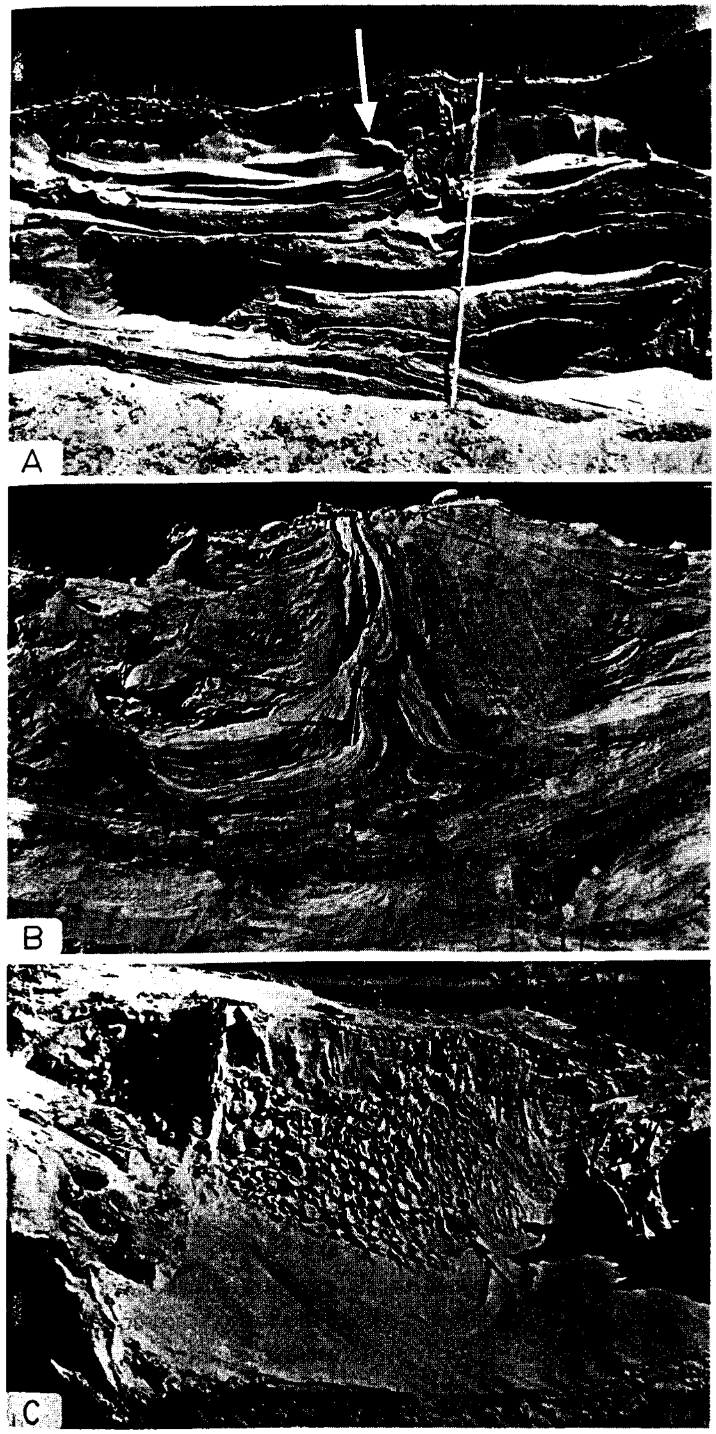

Fig. 3. A. Convolute stratification showing broad synclinal troughs and a narrow diapir. Note the dyke extending from the diapir into the synclinal trough (arrowed). Scale 3.5 m long. B. Diapir within convolute stratification displaying subvertical laminae. Pencil (arrowed) is 15 cm long. C. The outer wall of a diapir displaying bubble-like penetrations into the synclinal portion of a convolute unit (sediment filling the synclinal trough has been removed by wind erosion). Arrow shows position of lens cap (diameter 6 cm).

deformed subvertical laminae of cleaner fine sand (Fig. 3B). In some cases the diapiric structures appear as anticlines which do not completely penetrate overlying beds, although by digging further into the exposure complete penetration can be normally observed. This suggests that some diapirs are elongate cones rather than sheets. Where present, stratification within the synclines is undisturbed, except where it is bent upwards at the edges. The bases of the synclines are in many cases defined by an abrupt boundary with underlying silty fine sand. Small dykes of silty fine sand were observed to extend from diapirs into the sand in synclines (Fig. 3A, arrowed). Where the sand had been blown out of one syncline, smaller scale, bubble-like penetrations were observed on the outer wall of a diapir (Fig. 3C).

Underlying convolute stratification are cross-stratified sands which, in some cases, are also deformed but in other cases are entirely undisturbed. The boundaries between convolute units and underlying sediments are commonly sharp, suggesting an erosional surface. The sediments immediately above the convolute units are primarily silty-fine sands, like those in the diapiric structures, and contain ball and pillow structures, and/or dish structures. Two types of lateral transition between convolute units and undeformed sediments were observed: (1) abrupt transitions, marked by a sharp boundary where the underlying contact curves upwards to the top of the exposure; and (2) gradational boundaries, where the convolute units pass laterally into climbing ripple drift interbedded with massive sands, the amplitudes of the folds decreasing towards the undeformed units. Convolute units exposed in plan appear as ellipsoidal troughs exceeding 3 m in length. Unfortunately, plan exposures are rare, so that it was not possible to determine whether they have a preferred orientation.

Ball and pillow structures

In all but two of the exposures studied ball and pillow structures were observed in units extending below the floor of the sand pit. They commonly occur in high concentrations and range in apparent diameter from several centimetres to seven metres. They show an overall trend of decreasing size upward in vertical sequence. The spacing of individual structures is generally less than 20 cm at their closest point, although this distance increases between larger structures. The sediment between balls and pillows is a silty fine sand which commonly contains subparallel, subvertical laminae which are similar to those in the diapirs associated with convolute stratification. The sediment between the largest structures also contains smaller ball and pillow structures. The smallest balls at the top of the sequence are surrounded by fine, silty sand containing dish structures, and appear as massive packets of slightly coarser sand with their bases defined by a dish-like lamination. The sediment within the majority of the larger ball and pillow structures is stratified with the stratification bent upwards at their margins towards a subvertical axial plane. An exception to this deformation style is shown in Fig. 4, in which the internal stratification is bent downwards.

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Fig. 4. Ball and pillow structures. The pillow on which the 20 cm scale is resting is unusual in that internal stratification is bent downwards at the edges.

In two exposures ball and pillow structures occur in continuous vertical sequence with underlying units of convolute stratification (Fig. 5). In another exposure, convolute stratification occurs along a surface which dips towards a unit of ball and pillow structures and is inferred to underly the latter, although the actual transition could not be observed.

Fig. 5. Convolute stratification overlain by ball and pillow structures and dish structures (dishes not visible in photo). The black portion of the shovel handle is 30 cm long.

Dish structures

Dish structures occur primarily above ball and pillow structures in silty, fine sands. The transition between the ball and pillow structures and dishes is commonly gradual, occurring over a vertical distance of several decimetres (Fig. 6). The lowermost dishes are between ball and pillow structures whereas the uppermost balls and pillows are surrounded by sediment containing dish structures. The uppermost balls and pillows, with bases defined by dish-like laminae, differ from true dish structures in their larger size, coarser sediment above the laminae and the greater thickness of the basal laminae. In vertical sequence dishes exhibit an upward decrease in concavity and upward increase in their apparent length and vertical spacing.

The textural characteristics of the dish structures were observed with a binocular microscope in samples impregnated with shellac and cut at right angles to the dish laminae. The sediment surrounding the dish laminae is poorly sorted silty fine sand (Fig. 7, labelled "*a*"). The individual laminae consist of a zone, approximately 1 mm thick, which contains fine sand and is largely lacking in silt and clay (Fig. 7, labelled "*b*"). This zone passes gradationally downwards into the poorly sorted sediment, whereas its upper margin is sharply defined by a very thin lamina (less than 0.1 mm)

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Fig. 6. Upward transition from ball and pillow structures to dish structures. Note the dish-like laminae marking the base of the small, uppermost ball and pillow structures. Scale is 20 cm long.

of clay- to silt-sized sediment (Fig. 7, labelled "c"). Immediately above this lamina the sediment is identical to that below the dish structure. The dishes themselves consist of both the zone of relatively well sorted fine sand and the overlying clay/silt lamination. Between the upturned edges of adjacent dishes that do not

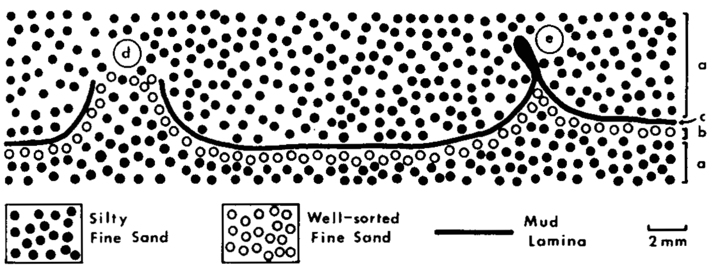

Fig. 7. Schematic illustration of the distribution of sediment types in dish structures, showing: a = poorly sorted silty fine sand above and below the dish laminae; b = well-sorted fine sand, sharply overlain by c = a thin lamina of mud-size sediment. A gradual transition between dish laminae is labelled "d" while a considerably thickened mud lamina at dish intersection is labelled "e".

cross-cut, the sandy laminae pass gradually into the poorly sorted sediments (Fig. 7, labelled "d"). Where there is an intersection between adjacent dishes, the thin clay/silt lamina thickens (Fig. 7, labelled "e").

The plan morphology of dish structures was observed by excavating horizontal terraces into the face of the exposure and by digging down from the top where a unit of dish structures is near the surface. The dishes commonly have an elliptical plan form, although circular and more complex shapes were also observed. Long axis orientations of elliptical dishes are summarized in Fig. 8, showing a preferred orientation approximately normal to the local paleocurrent direction (determined from type A climbing ripple drift, stratigraphically below the deformed sediments).

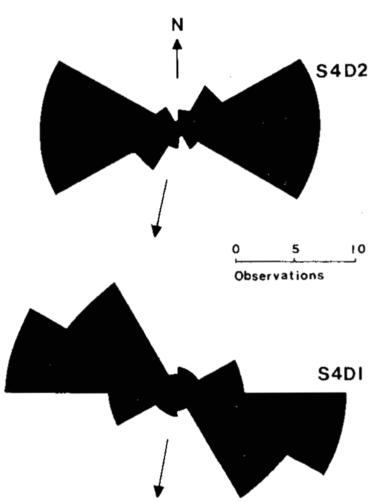

Fig. 8. Orientation data for two sets of dish structure long axes. (Set S4D2 was collected approximately 50 cm above set S4D1, within the same dish unit). Arrows indicate the paleocurrent direction determined from type A climbing ripple drift which stratigraphically underlies the dishes.

DISCUSSION

The convolute stratification descri
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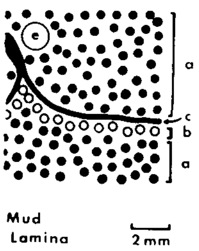

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DISCUSSION

The convolute stratification described above is similar to that discussed by Davies (1965) and Lowe (1975, p. 187) who recognized diapirs as vertical channels through which fluidized sediment passed during rapid dewatering. The silty-fine sand underlying synclinal troughs and filling the diapirs was probably deposited rapidly and developed an excessive pore water pressure as continuing sedimentation increased the load. In some cases the water which caused fluidization may have been derived from melting ice, buried by deposition on the subaqueous fan. When the pore water pressure exceeded some critical value the silty-fine sand under-went fluidization and was locally ejected upwards through more cohesive overlying sediments, forming the diapirs. The synclinal troughs resulted from subsidence of sediment between the diapirs. Sills and dykes of silty fine sand are preserved where mobile sediment locally broke through the walls of the diapirs (Fig. 3A). The small bubble-like structures (Fig. 3C) may have developed during the final stages of deformation as the material within the diapirs lost water, and became more viscous, plugging the diapirs. The less intense fluid discharges then passed through the relatively thin diapir walls, causing a mud lining to deform hydroplastically into the bubble-like structures.

The observation that ball and pillow structures overly convolute stratification suggests that the two structures are genetically related. Most models for the formation of ball and pillow structures assume that the internal stratification was bent upwards while sinking into the underlying sediment (Kuenen, 1958). In addition, however, it is postulated here, that vertically flowing columns of fluidized sediment passing upwards through the diapirs exerted sufficient force to deform overlying strata into ball and pillow structures. This mechanism was observed during experimental studies by Butrym et al. (1964). The inverted pillow in Fig. 4 is believed to have formed in this way, but after initial deformation the pillow rotated without undergoing further deformation.

The upward decrease in the size of the ball and pillow structures is attributed to a tendency for the diapirs to bifurcate upwards, probably due to anisotropy in the strength of the sediments they intruded. Diapir bifurcation is documented in Fig. 9, in which a single diapir broadens and splits into two after penetrating and convoluting cross-stratified sediments. As a result of such upward bifurcation, overlying cohesive sediments may be disrupted into progressively smaller pieces at higher levels, forming increasingly smaller ball and pillow structures. Bifurcating systems of diapirs are rarely preserved, however, because of the transient, liquefied nature of the diapirs, whereas the ball and pillow structures have a high preservation potential.

Lowe and LoPicollo (1974) concluded that dish structures form when upward escaping pore water encounters an impermeable lamina which forces the flow to move laterally. Lateral flow continues until the lamina is breached, forming the upturned edges of the dish. In the Stittsville ridge dish structures form in silty, fine

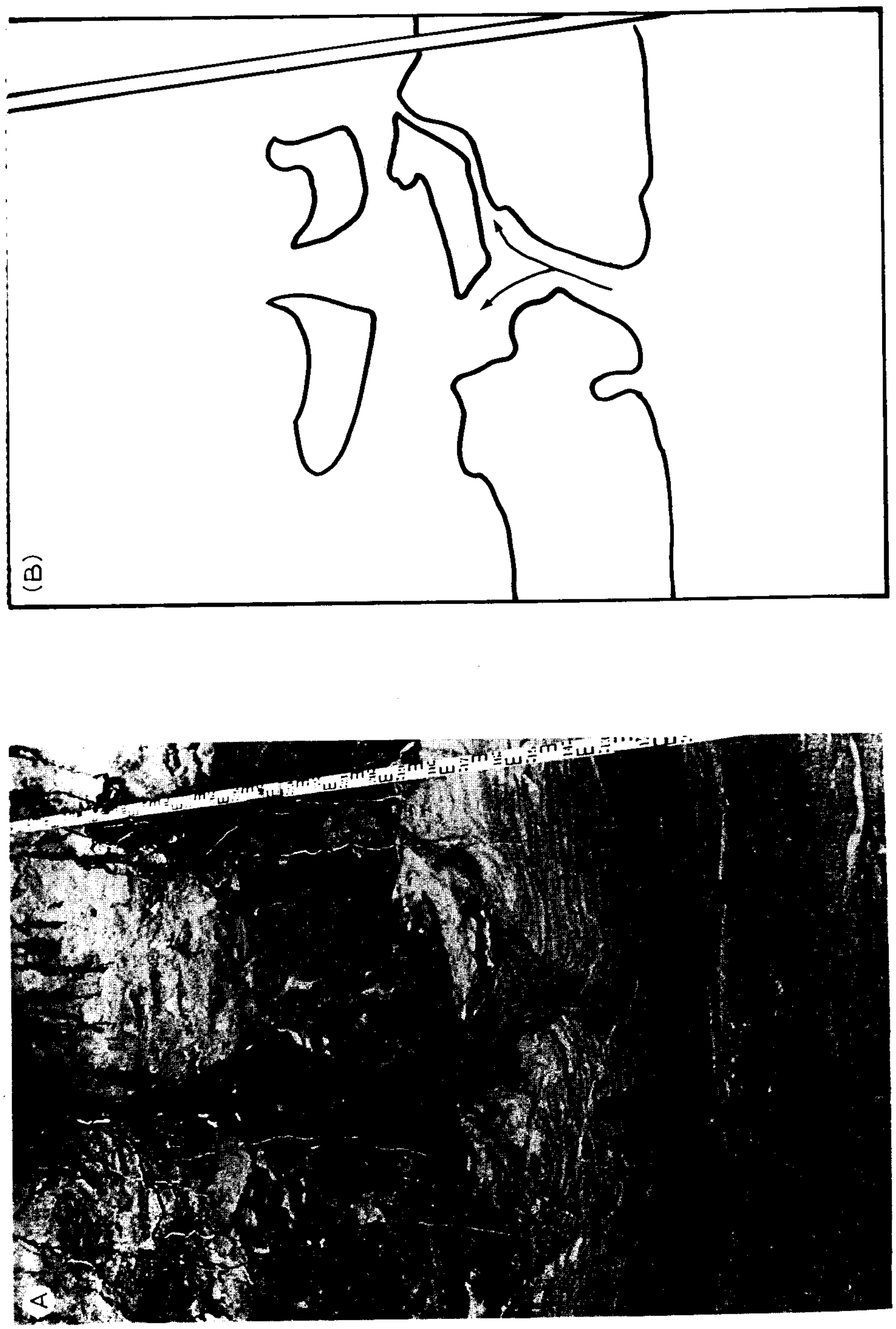

Fig. 9. A. Convolute stratification overlain by ball and pillow structures and dish structures (dishes not visible on photograph). B. Sketch of adjacent photograph emphasizing bifurcation of the principal diapir above the convolute unit (shown by arrows). Smallest scale divisions are 1 cm.

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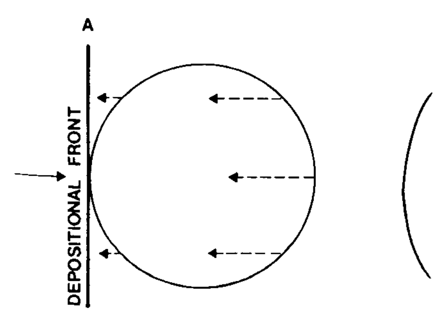

Fig. 10. Schematic illustration showing the pro
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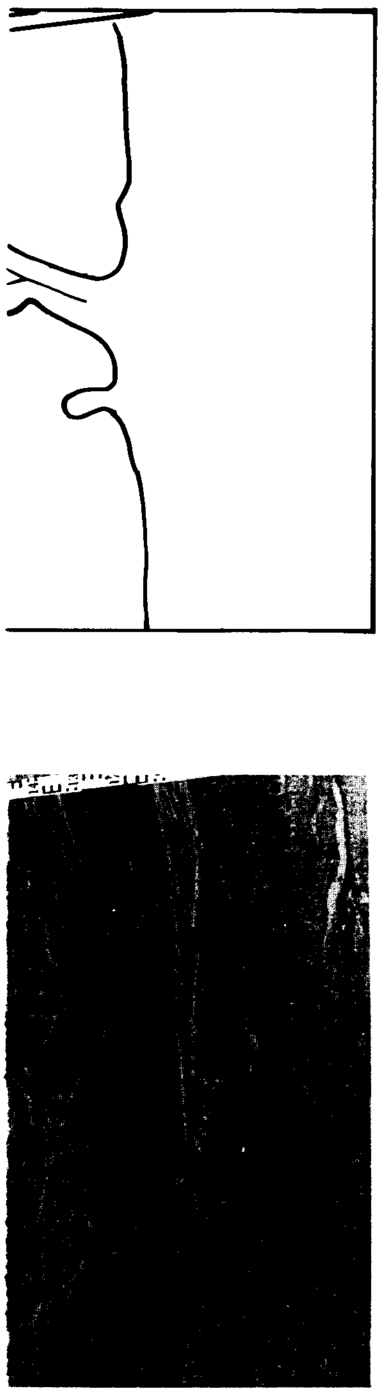

Fig. 9. A. Convolute stratification overlain by ball and pillow structures and dish structures (dishes not visible on photograph). B. Sketch of adjacent photograph emphasizing bifurcation of the principal diapir above the convolute unit (shown by arrows). Smallest scale divisions are 1 cm.

sand that is believed to have passed through the diapirs, accumulating above the then sinking ball and pillow structures and just below the sediment–water interface. An analogous situation is the accumulation of mud above diapirs, forming mud boils on the sediment surface. In the present case, however, sediment accumulated as a relatively extensive mass in a basin formed by the sinking of underlying material. The occurrence of dish structures in these deposits suggests that fluidized sediment which passed from the diapirs became liquified (Lowe, 1976), probably due to a reduction in the porewater pressure. The origin of the laminae which are necessary for the formation of dish structures is problematic in sediments which were emplaced as proposed for the Stittsville Ridge. It seems most likely that these dish structures formed from laminae which developed: (1) as consolidation laminae (Lowe, 1975) by the processes of elutriation and deposition during water escape; or (2) during downslope flowage of the liquefied sediment by a process which caused segregation of fines along horizontal planes within the flow; or (3) by some combination of these processes. However, it is difficult to postulate a mechanism for the formation of consolidation laminae in structureless sand. The solution to this problem is made more difficult by the fact that the textural clues to the origin of the original laminae were probably masked during dish formation.

The elliptical form and preferred orientation of the dish structures at Stittsville are attributed to downslope flowage of the liquefied sediments during dish formation (Fig. 10). The initial plan form of the dish structures is assumed to have been approximately circular, presuming that their development is isotropic, i.e., the rate of fluid escape is constant and uniform within the sediment and that the restricting lamination is of uniform composition. Figure 10A shows an undeformed dish structure, which subsequently moves downslope to the left, with the flowing liquefied sediment, and becomes deformed (Fig. 10B). It is presumed that as in subaerial grain flows, movement of thick, liquefied flow initially ceases at the downslope end of the flow, followed by cessation of movement at locations which are progressively upslope. This can be visualized as a "depositional front" which appears to move upslope in the flow. The heavy dark line in Fig. 10 represents such a depositional

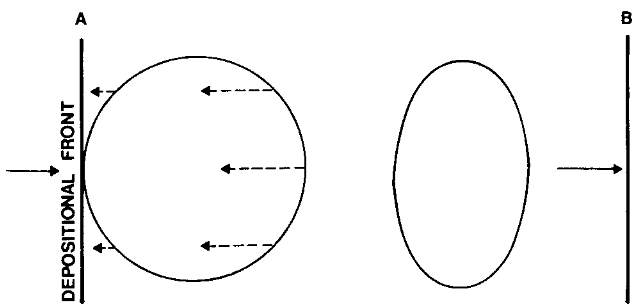

Fig. 10. Schematic illustration showing the proposed mechanism for modification of the plan form of dish structures by lateral compression at the cessation of downslope flowage. See text for explanation.

front, which moved in the upslope direction (to the right as indicated by the large solid arrows), and along which movement of the liquefied flow ceases. The dashed lines with arrows indicate the downslope path through which each respective point on the dish will move as the depositional front traverses it. The front reaches the downslope edge of the dish before it reaches the upslope edge, so that the latter will continue moving after the former has stopped. The result is a compression of the dish structure to an elliptical form with its long axis perpendicular to the downslope direction. This is consistent with the observed relationship between measured dish long axes and paleocurrent directions.

SUMMARY

Figure 11 depicts a hypothetical model summarizing the interpretation of each structure and the probable development of the observed upward sequence: convolute stratification overlain by ball and pillow structures, in turn overlain by dish structures. This sequence has been observed in the field and is regarded as an "ideal sequence", which may or may not occur in a complete form elsewhere.

Stage 1 of the model (Fig. 11A) shows the pre-deformational sequence of beds of massive and cross-stratified fine sand and silty fine sand within the subaqueous

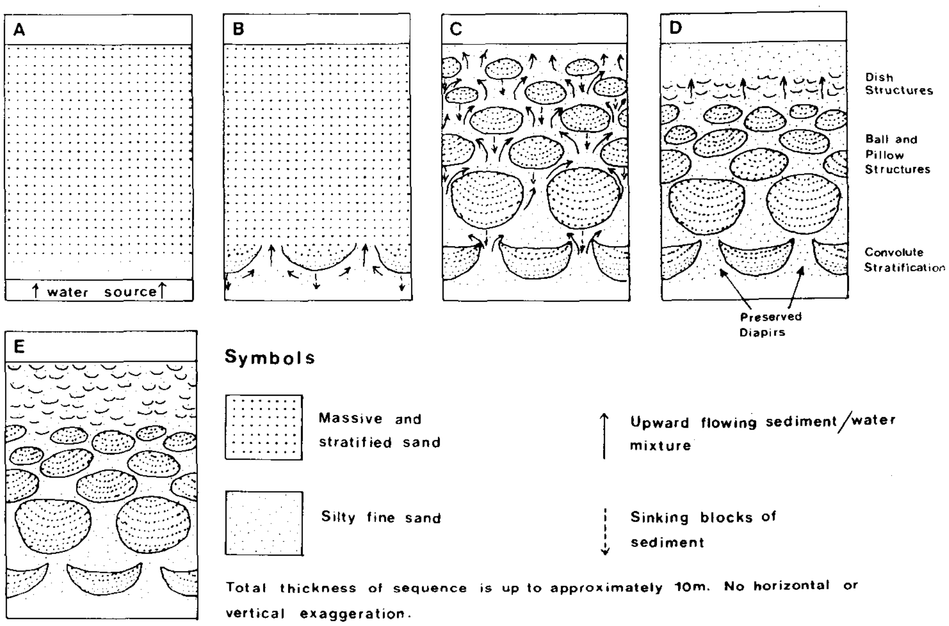

Fig. 11. A hypothetical model for the formation of the upward sequence of soft-sediment deformation structures observed in the subaqueous outwash of Stittsville Ridge. The sequence consists of convolute stratification, ball and pillow structures and dish structures. See text for detailed explanation.

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external shock initiates rapid dewate
to initiate fluidization of the basal sil
In stage 2 (Fig. 11B) rapid dev
fluidization of the lower beds of rela
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stage vertical fluidization channels (
the diapirs sinking downwards, to fo
stratification in the basal unit.
Stage 3 (Fig. 11C) involves the di
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disrupt the overlying beds into large
turned upward due to the frictional
and pillow structures. Clearly the dis
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then sink downwards, in response to
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symmetrically, but a few develop as
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progressively, forming increasingly s
tures. The diapirs finally terminate a
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prevailing at this level, the pore water
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supported by the escaping fluid) and
At stage 4 of the model (Fig. 11D
maximum thickness as the addition o
not before, the material may slowly
dewatering continues downslope flow
with long axes oriented normal to th
marks the completion of dewatering.
observed in the field (Fig. 11E).

CONCLUSION

The sequence and characteristics
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the liquefied flow ceases. The dashed
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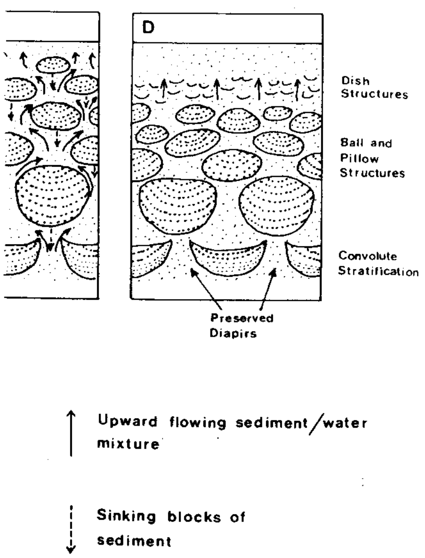

approximately 10m. No horizontal or

ward sequence of soft-sediment deformation
le Ridge. The sequence consists of convolute
. See text for detailed explanation.

outwash fan (cross strata are not shown for the sake of simplicity). The lowermost silty fine sands either contain abundant primary pore water (i.e., trapped at the time of deposition) or they are overlying a source of water such as sands undergoing consolidation or melting buried ice. The fine sediments remain stable until an external shock initiates rapid dewatering or until the pore water pressure is sufficient to initiate fluidization of the basal silty fine sediments.

In stage 2 (Fig. 11B) rapid dewatering of the sediment has begun with the fluidization of the lower beds of relatively impermeable silty fine sand, which flows laterally to points where it can locally penetrate through the overlying strata. At this stage vertical fluidization channels (diapirs) are established, with sediment between the diapirs sinking downwards, to form the broad synclinal troughs of the convolute stratification in the basal unit.

Stage 3 (Fig. 11C) involves the disruption of overlying beds by the diapirs. Near the base, just above the convolute stratification, a few large, widely spaced diapirs disrupt the overlying beds into large detached blocks. The edges of these blocks are turned upward due to the frictional drag exerted by the vertical flow, forming ball and pillow structures. Clearly the distinction between synclines in a convoluted unit and ball and pillow structures is somewhat arbitrary, and is based on the degree of lateral continuity of the synclinal blocks. The detached ball and pillow structures then sink downwards, in response to the removal of underlying sediment, distorting or completely destroying the transient diapirs. In most cases the structures sink symmetrically, but a few develop asymmetry or are overturned, probably due to interference from other sinking masses. At higher levels the diapirs bifurcate progressively, forming increasingly smaller, more numerous ball and pillow structures. The diapirs finally terminate at the fan surface, where much of the fluidized sediment which passed through the diapirs accumulates at the top of the sediment column, above the sinking balls and pillows. Under the lower confining pressures prevailing at this level, the pore water pressure decreases so that the sediment passes from a fluidized state to a liquefied state (i.e., the sediment is no longer wholly supported by the escaping fluid) and dish structures begin to form.

At stage 4 of the model (Fig. 11D) the uppermost liquefied unit has reached its maximum thickness as the addition of material from below ceases. At this point, if not before, the material may slowly flow down the gentle slope of the fan. As dewatering continues downslope flowage deforms the dishes into elliptical structures with long axes oriented normal to the slope. The cessation of downslope flowage marks the completion of dewatering, having produced the sequence of structures observed in the field (Fig. 11E).

CONCLUSION

The sequence and characteristics of soft-sediment deformation structures described in this paper suggest that the three types of structure are, in this case, genetically related. Convolute stratification and ball and pillow structures form due to penetration of cohesive beds of sediment by fluidized sediment under load. Penetration generates the diapiric structures between broad synclines which together comprise convolute stratification. With penetration to higher levels, the passage of fluidized sediment through a bifurcating diapir system breaks the overlying cohesive beds into progressively smaller ball and pillow structures. Internal stratification is bent upwards during initial penetration, while further deformation may or may not occur as these structures sink downwards. Dish structures form at the top of the sequence in sediment which has passed out of the diapirs, accumulating at the water–sediment interface. Deformation of dish structures with the cessation of downslope flowage forms elliptical dishes which indicate the sense of the paleoslope direction.

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